Finding the Higgs boson

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FNAL LHC School, Lecture 2

- Properties of the Higgs boson

  Theoretical uncertainties & motivations for precision measurements

- Higgs production at the Tevatron and LHC

Who needs a Higgs?

- Gives masses to W, Z, and fermions in gauge invariant fashion
- Unitarizes VV$\rightarrow$VV scattering
  - (More in Lecture 3)
- Makes precision electroweak data consistent

But….

- Higgs mechanism doesn't explain masses or flavor structure
  - It accommodates them
- Higgs mass is quadratically sensitive to physics at high scales
  - (More in Lecture 3)
- Higgs potential stable only for certain Higgs masses
  - (More in Lecture 3)

Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

v=246 GeV

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos

Review of Higgs Couplings

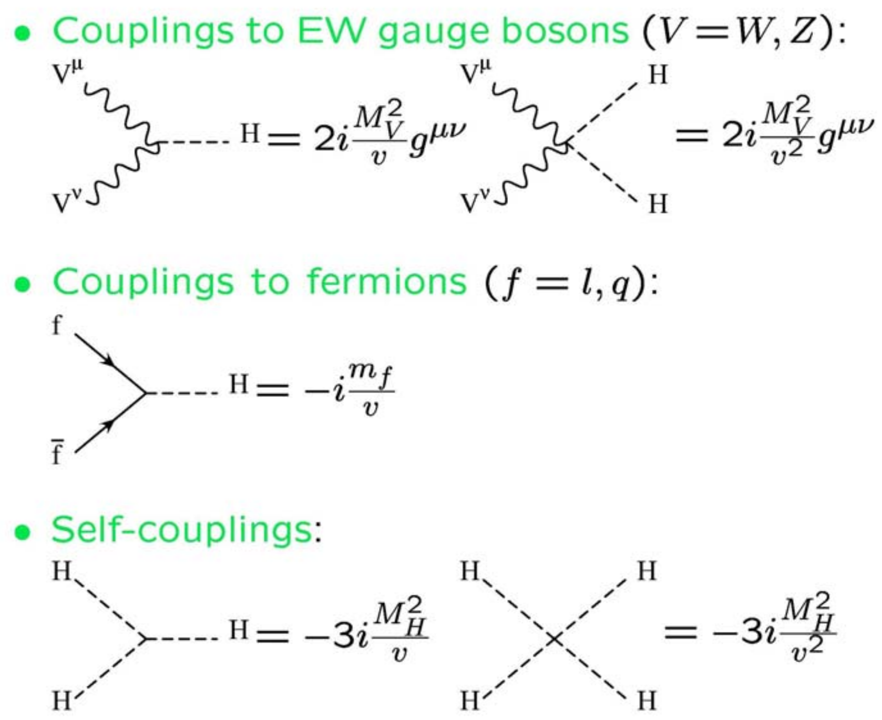
- Higgs couples to gauge boson masses

$$L = gM_W W^{+\mu} W_\mu^{-} h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h + \ldots.$$

- Only free parameter is Higgs mass!
- Everything is calculable….***testable theory***

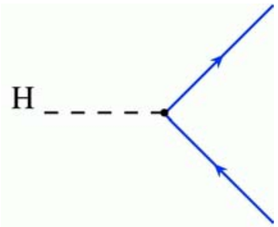
$$\boxed{g^2 = \frac{G_F}{\sqrt{2}} 8M_W^2 = \frac{e^2}{\sin^2\theta_W} = \frac{4\pi\alpha}{\sin^2\theta_W}}$$

Review of Higgs Boson Feynman Rules



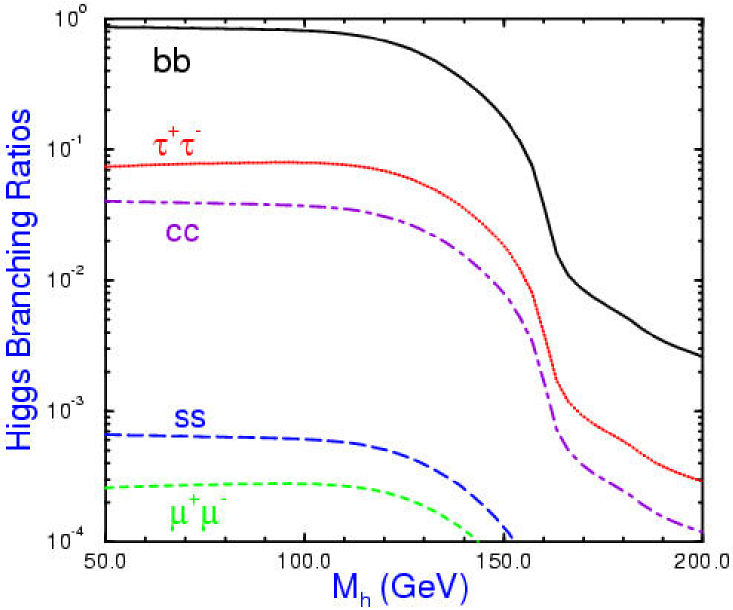
- Higgs couples to heavy particles
- No tree level coupling to gluons (g) or photons (γ)
- $M_h^2 = 2v^2\lambda \Rightarrow$ large M_h is strong coupling regime

Higgs Decays



$$\Gamma(h \to f\bar{f}) = \frac{N_c G_F m_f^2 M_h}{4\sqrt{2}\pi}\beta^3$$

$$\beta_f = \sqrt{1 - \frac{4m_f^{\ 2}}{M_h^{\ 2}}}$$



- $h \to ff$ proportional to m_f^2

$$\frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)} = N_c \left(\frac{m_b^{\ 2}}{m_\tau^{\ 2}}\right)\left(\frac{\beta_b}{\beta_\tau}\right)^3$$

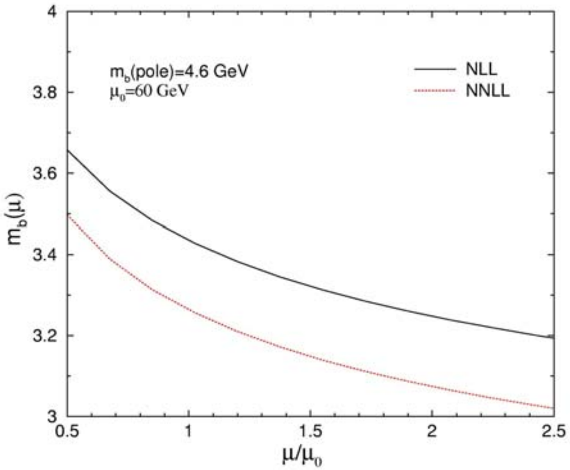
- β^3 typical of scalar
  (pseudo-scalar decay $\approx\beta$)

For M_h<$2M_W$, decays to $b\bar{b}$ most important

QCD Corrections to $h \to Q\overline{Q}$

- Tree level: $\Gamma(h \to Q\overline{Q})_{tree} = \frac{3 G_F M_h}{4\sqrt{2}\pi} M_Q{}^2 \beta_Q{}^3$
- Add QCD: $\Gamma(h \to Q\overline{Q})_{QCD} = \frac{3 G_F M_h}{4\sqrt{2}\pi} \overline{m}_Q{}^2 (M_h) \beta_Q{}^3 \left(1 + 5.67 \frac{\alpha_s(M_h)}{\pi} + \ldots\right)$
- Large logs absorbed into running $\overline{\text{MS}}$ mass:

$$m_b(\mu^2) = m_b(m_b{}^2)\left(\frac{\alpha_s(m_b^2)}{\alpha_s(\mu^2)}\right)^{-12/23}$$



Higgs Decays to Gauge Bosons

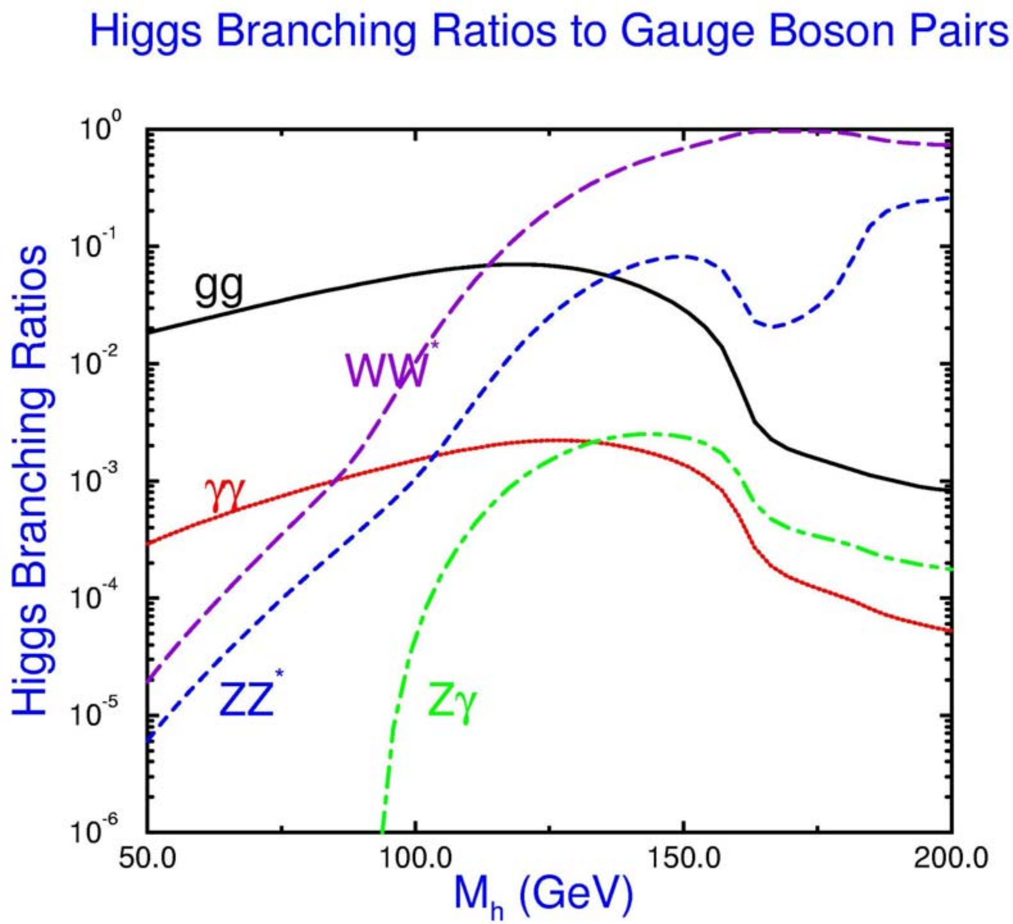
- h $\rightarrow$gg sensitive to top loops
  - Remember no coupling at tree level
- h $\rightarrow$ $\gamma\gamma$ sensitive to W loops, only small contribution from top loops
- h $\rightarrow W^+W^- \rightarrow$ffff has sharp threshold at 2 M_W, but large branching ratio even for M_h=130 GeV

$$\boxed{\Gamma(h \rightarrow VV) = \frac{G_F M_h^3}{8\sqrt{2}\pi}\delta_V \beta(..)}$$

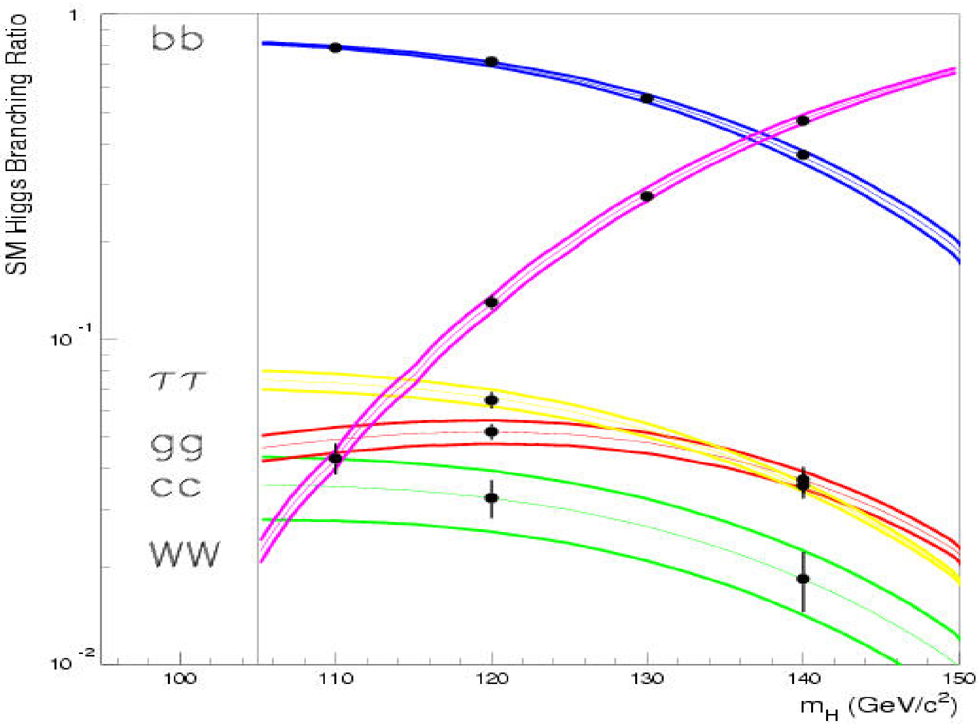
$$\delta_{W,Z} = 2,1$$

Cubic in M_h, so for heavy Higgs, decays to vector boson dominate

Decays to Gauge Bosons



Status of Theory for Higgs BRs



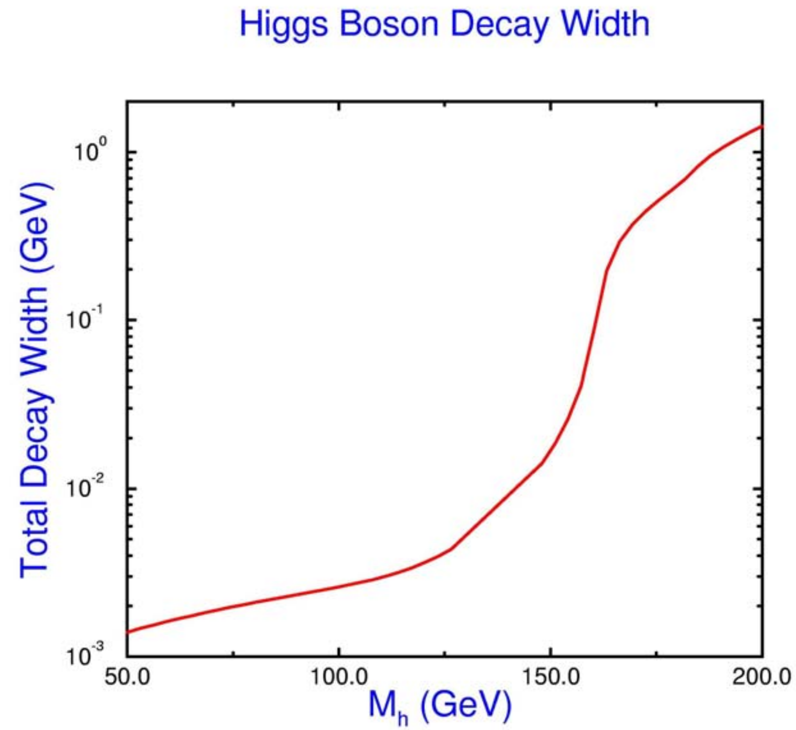
- ➢**Bands show theory errors**
- ➢**Largest source of uncertainty is b quark mass**

Data points are e^+e^- ILC at $\sqrt{s}$=350 GeV with L=500 fb^{-1}

Total Higgs Width

- Total width sensitive function of M_h
- Small M_h, Higgs is narrower than detector resolution
- As M_h becomes large, width also increases
  - No clear resonance
  - For M_h ~1.4 TeV, Γ_{tot} ~M_h

$$\Gamma(h \to W^+W^-) \approx \frac{\alpha}{16 \sin^2\theta_W} \frac{M_h{}^3}{M_W{}^2}$$
$$\approx 330 GeV \left(\frac{M_h}{1TeV}\right)^3$$



•Higgs branching ratios easily computed with HDECAY program to NLO

•http://mspira.home.cern.ch/mspira/proglist.html

Higgs Searches at LEP2

- LEP2 searched for $e^+e^- \to Zh$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma \sim \beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***

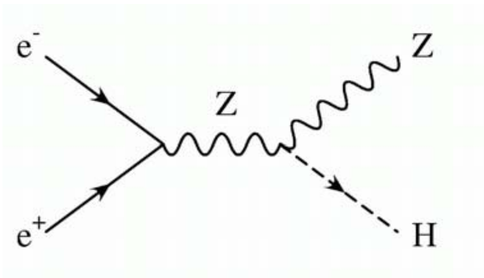
  $P_{e-}=\sqrt{s}/2(1,0,0,1)$

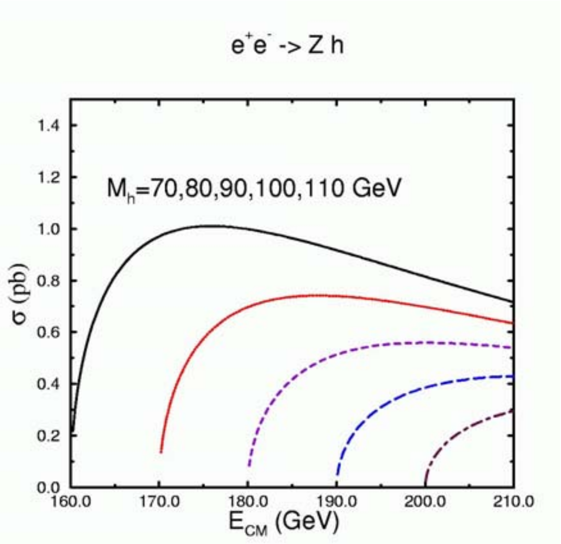
  $P_{e+}=\sqrt{s}/2(1,0,0,-1)$

  $P_Z=(E_Z, \vec{p}_Z)$
- Momentum conservation:

  $(P_{e-}+P_{e+}-P_Z)^2=P_h^2=M_h^2$

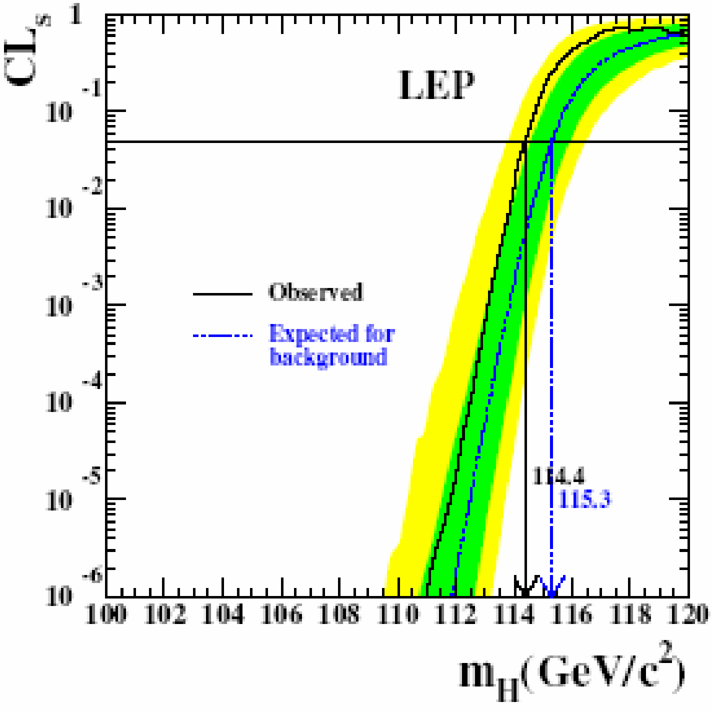
  $s-2\sqrt{s}\,E_Z+M_Z^2= M_h^2$
- LEP2 limit, ***M_h > 114.1 GeV***





Higgs at LEP2

- Higgs decays predominantly to $b\bar{b}$
- LEP-2 searched in many channels
  - $b\bar{b}jj$, $b\bar{b}l^+l^-$, $b\bar{b}\nu\bar{\nu}$, $\tau^+\tau jj$, jjjj
- Z branching ratios
  - e^+e^- (3.3%)
  - $b\bar{b}$ (15%)
  - $\nu\bar{\nu}$ (20%) invisible
  - jj (the rest)



Higgs production at Hadron Colliders

- Many possible production mechanisms; Importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
- Importance varies with Higgs mass
- Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson

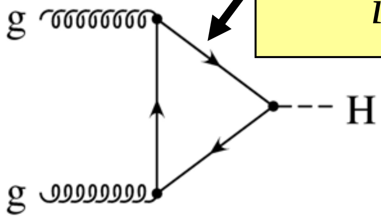
Production in Hadron Colliders

- Gluon fusion
  - Largest rate for all M_h at LHC
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa λ_t
- Lowest order cross section:

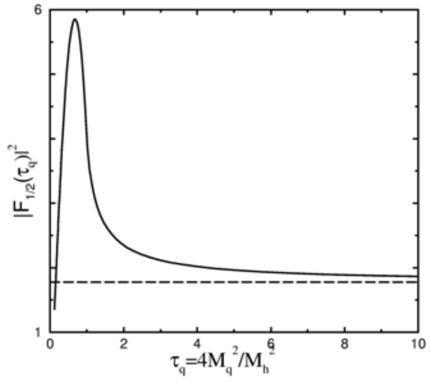
$$\hat{\sigma}_0(gg \to h) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta(M_h{}^2 - \hat{s})$$

  - $\tau_q = 4M_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \to (M_b/M_h)^2 \log(M_b/M_h)$
  - Heavy Quarks: $F_{1/2} \to -4/3$

In SM, b-quark loops unimportant



Largest contribution is top loop



Rapid approach to heavy quark limit

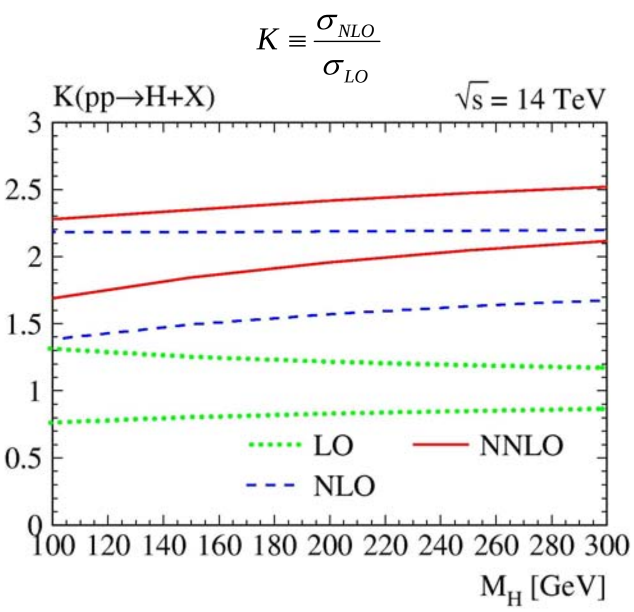
Gluon fusion, continued

- Integrate parton level cross section with gluon parton distribution functions

$$\sigma_0(pp \to h) = \hat{\sigma}_0 z \int_z^1 \frac{dx}{x} g(x, \mu_F) g(\frac{z}{x}, \mu_F)$$

  - $z = M_h^2/S$, S is hadronic center of mass energy
- Rate depends on μ_R, μ_F
- Rate for gluon fusion independent of M_t for $M_t >> M_h$
  - Counts number of heavy fermions

NNLO, gg→h



Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

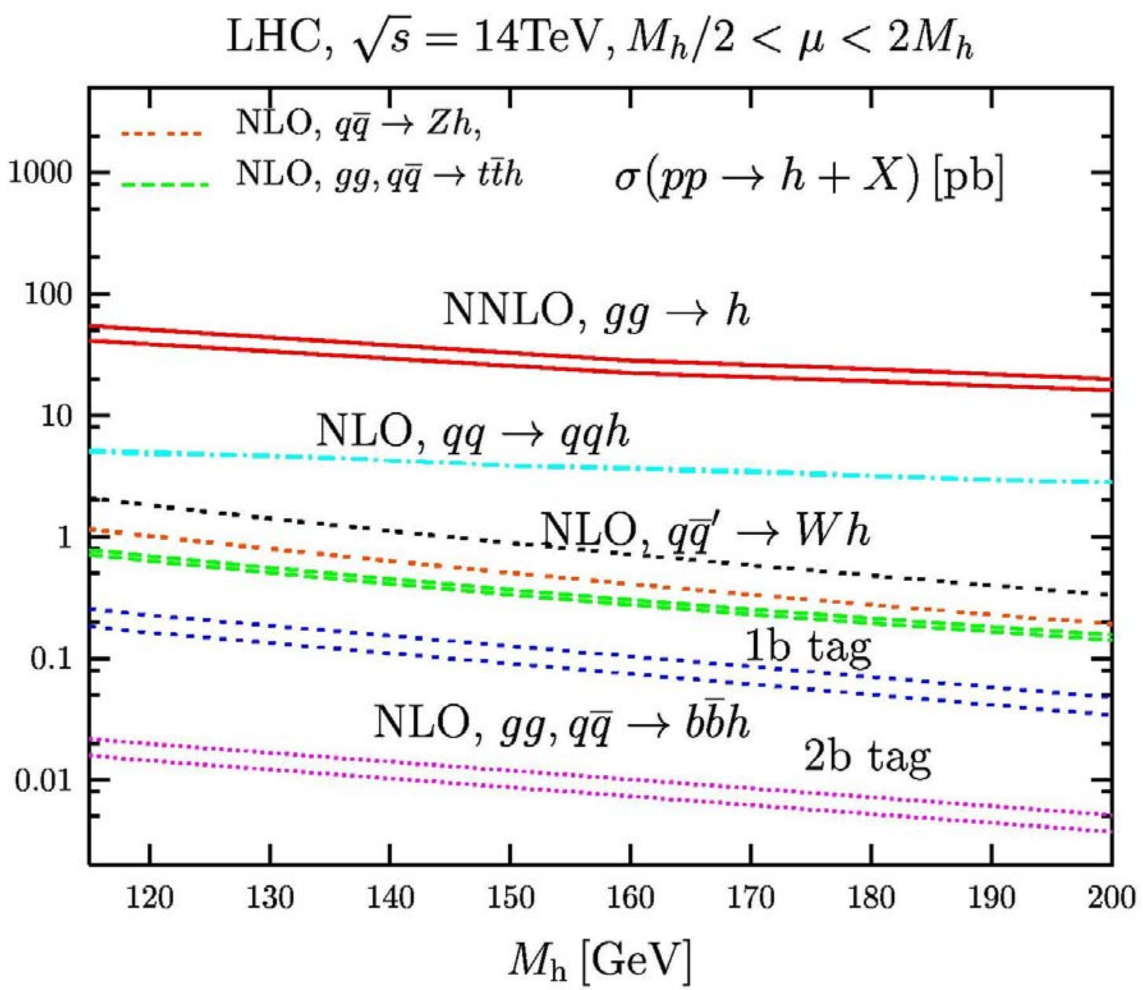
Bands show $.5M_h < \mu < 2\, M_h$

LO and NLO μ dependence bands don't overlap

μ Dependence used as estimate of theoretical uncertainty

NLO&NNLO results allow improved estimates of theoretical uncertainties

Higgs production at the LHC



Vector Boson Fusion

- $W^+W^- \to X$ is a real process:

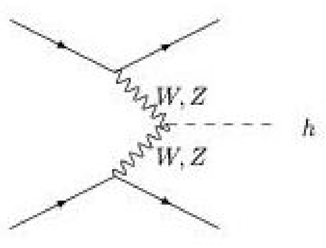
$$\sigma_{pp\to WW\to X}(s) = \int dz \frac{dL}{dz}\bigg|_{pp/WW} \sigma_{WW\to X}(zs)$$

- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$\int \frac{d\theta}{(k^2 - M_W{}^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W{}^2)^2}$$

Peaks at small θ

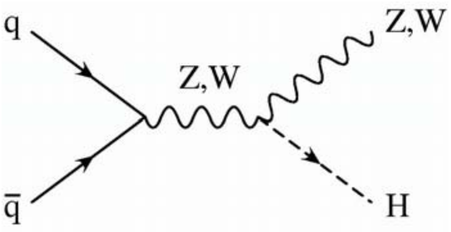
- Outgoing jets are mostly forward and can be tagged



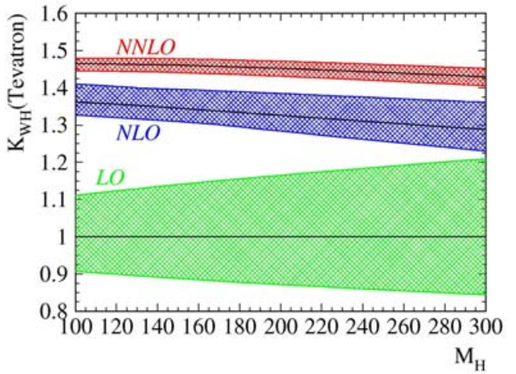
Idea: Look for h decaying to several different channels

Ratio of decay rates will have smaller systematic errors

W(Z)-strahlung



- W(Z)-strahlung ($q\bar{q}\rightarrow Wh$, Zh) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
  - Below 130-140 GeV, look for $q\bar{q}\rightarrow Vh, h\rightarrow b\bar{b}$
  - For M_h>140 GeV, look for $h\rightarrow W^+W^-$
- Theoretically very clean channel
  - NNLO QCD corrections: $K_{QCD}\approx 1.3$-1.4
  - Electroweak corrections known (-5%)
  - Small scale dependence (3-5%)
  - Small PDF uncertainties

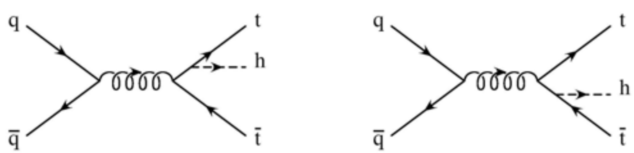


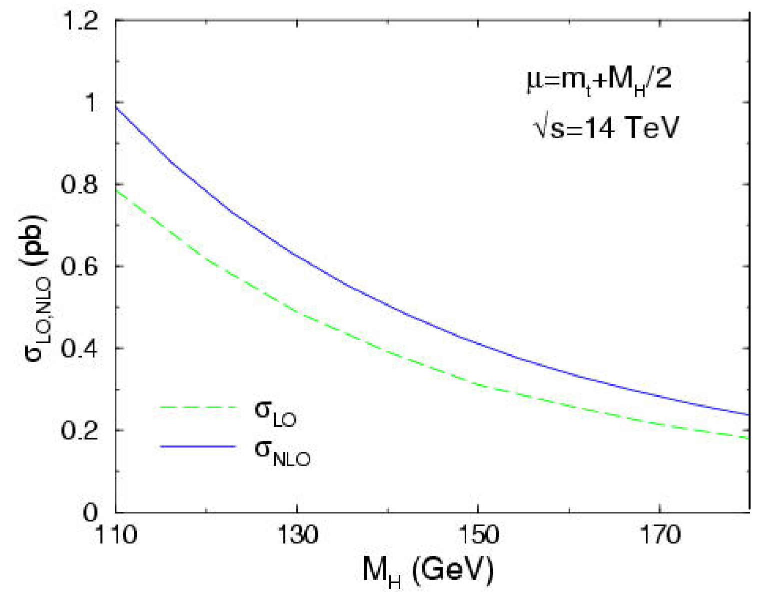
$t\bar{t}h$ Production

•$t\bar{t}h$ production unique channel to measure top quark Yukawa coupling

–$h \rightarrow tt$ never important

•bbh small in SM, but can be enhanced in SUSY models with large tan β



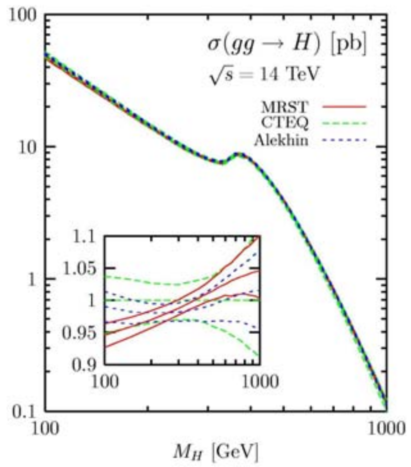


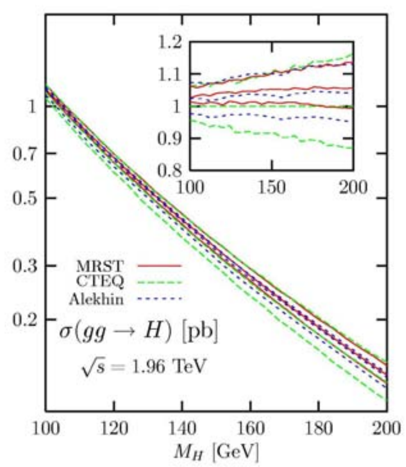
- Large QCD effects

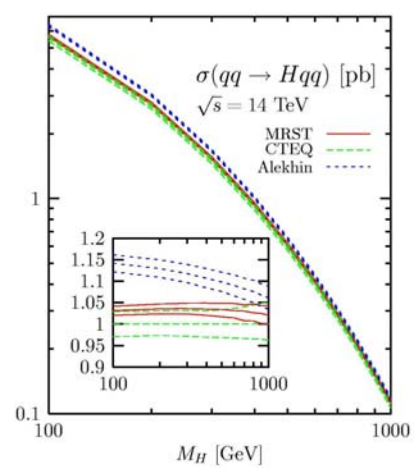
Higher order corrections

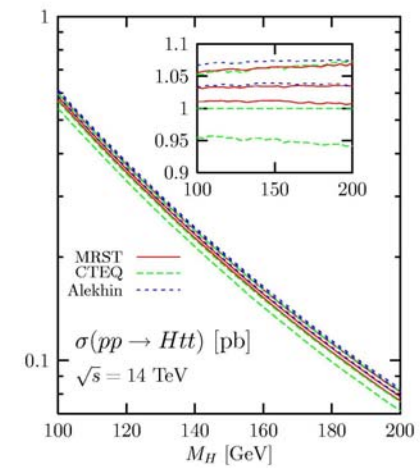
- QCD effects can be large
- Leading order cross sections have large uncertainties due to:
  - Renormalization/factorization scale dependence
  - Uncertainties from parton distribution functions (PDFs)
- Important modes have large QCD backgrounds
  - Often backgrounds only known to leading order

PDF uncertainties









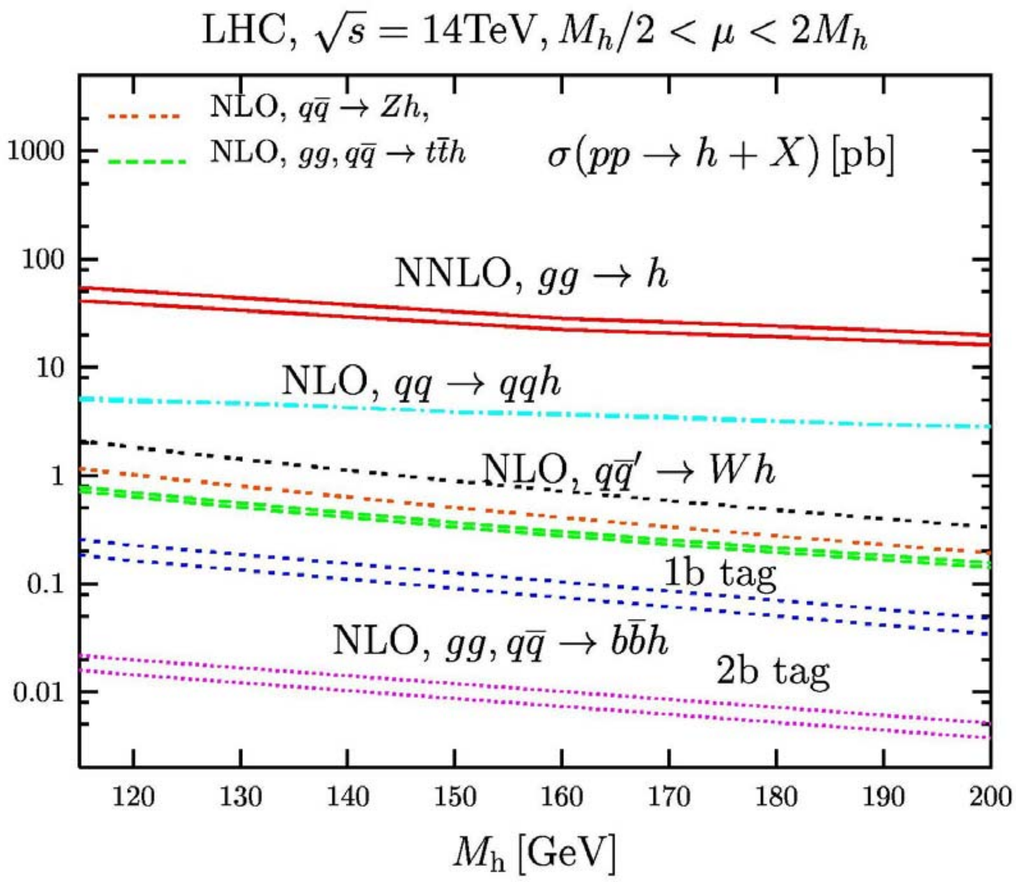
NLO PDFs with NLO cross sections!

Smaller PDF uncertainties in vector boson fusion ($\bar{q}q$ initial channel)

CTEQ6m: 40 PDFs for uncertainty studies

http://user.pa.msu.edu/wkt/cteq/cteq6pdf.html

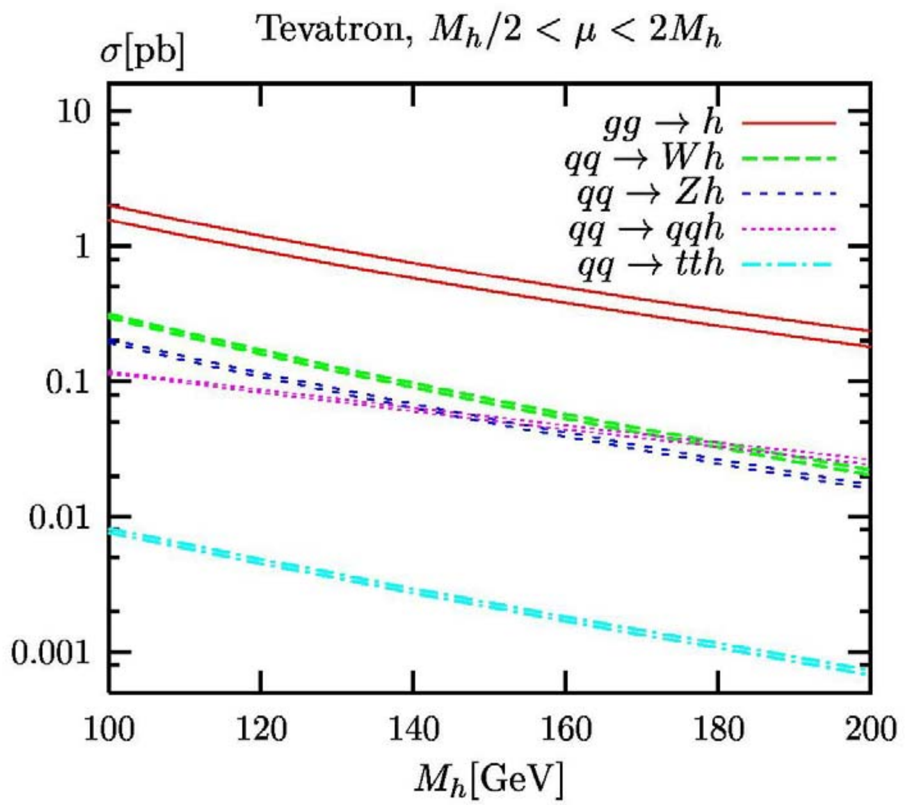
Production mechanisms at LHC



Bands show scale dependence

All important channels calculated to NLO or NNLO

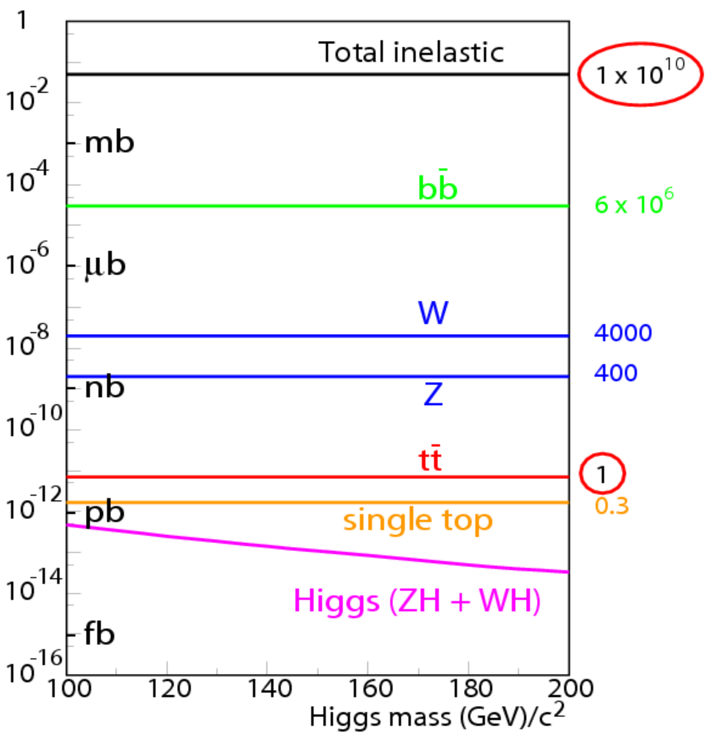
Comparison of rates at Tevatron



- ➢Luminosity goals for Tevatron: 6-8 fb^{-1}
- ➢Higgs very, very hard at Tevatron

Higgs at the Tevatron

- Largest rate, $gg \rightarrow h$, $h \rightarrow b\bar{b}$, is overwhelmed by background



$\sigma(gg \rightarrow h) \sim 1\ \text{pb} << \sigma(bb)$

Higgs at the Tevatron

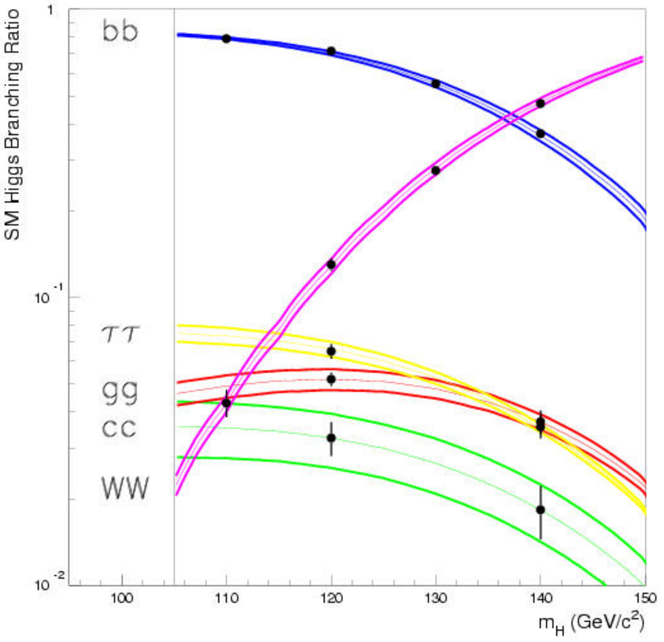
- Wh, $\bar{Z}$h production important for M_h<140 GeV, $h \to b\bar{b}$
  - Background from $Wb\bar{b}$, $Zb\bar{b}$
  - One of the few examples where both signal and background known to NLO

Wh, Zh and background in MCFM Monte Carlo to NLO

http:mcfm.fnal.gov

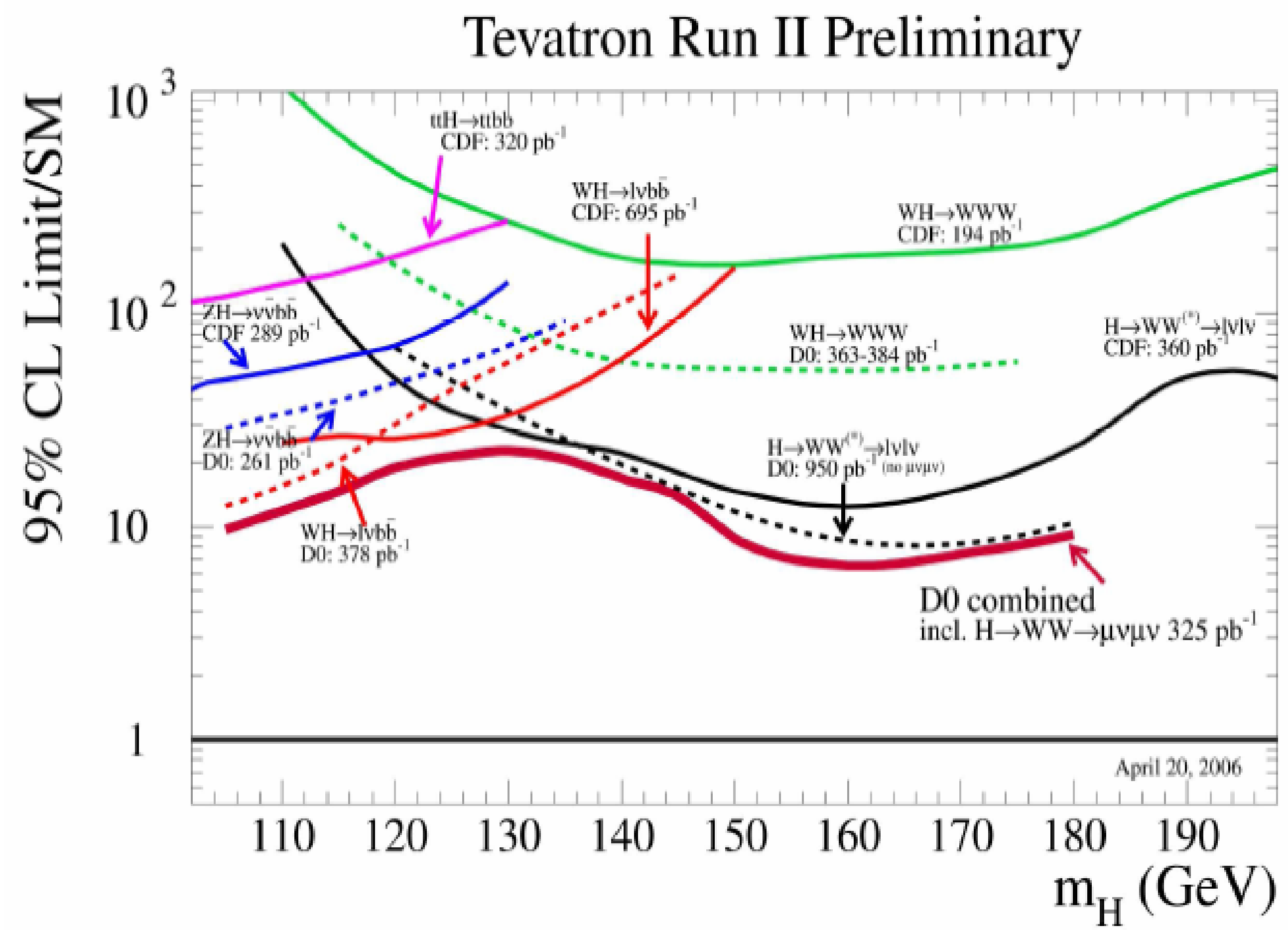
Search channels at Tevatron

- For heavier Higgs, look for $h \to W^+W^-$
- Searches for $gg \to h \to W^+W^-$ (dileptons)
- And $Wh \to W^\pm W^+W^-$ (2 and 3 leptons)

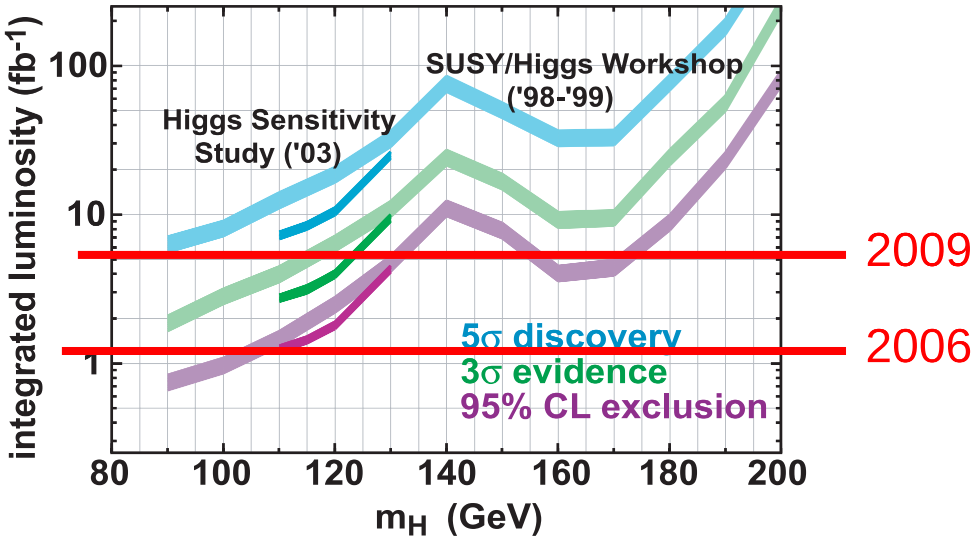


Requiring leptons reduces backgrounds

Tevatron Higgs Searches



Can the Tevatron discover the Higgs?



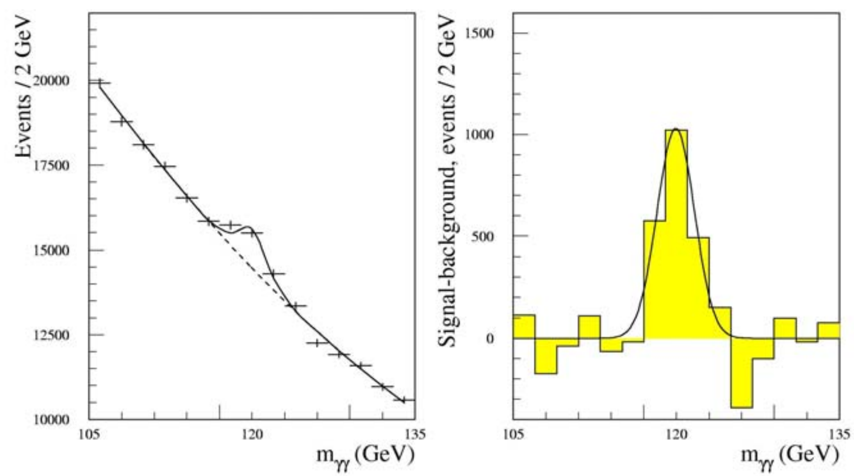
This relies on statistical combination of multiple weak channels

Search Channels at the LHC

$gg \to h \to b\bar{b}$ has huge QCD bkd: Must use rare decay modes of h

- ***$gg \to h \to \gamma\gamma$***
  - Small BR ($10^{-3} - 10^{-4}$)
  - Only measurable for $M_h < 140$ GeV
- Largest Background: QCD continuum production of $\gamma\gamma$
- Also from γ-jet production, with jet faking γ, or fragmenting to π^0
- Fit background from sidebands of data

M_h=120 GeV; L=100 fb^{-1}

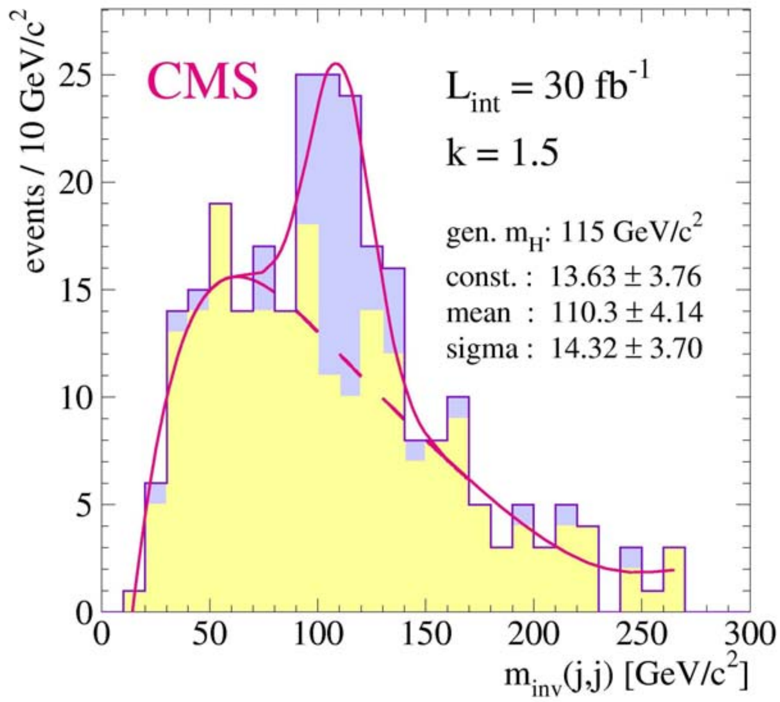


$S/\sqrt{B}$ = 2.8 to 4.3 σ

•Gives 1% mass measurement

$t\bar{t}h$ at the LHC

- $gg \to t\bar{t}h \to t\bar{t}b\bar{b}$
- Spectacular signal
  - $t \to Wb$
  - Look for 4 b jets, 2 jets, 1 lepton

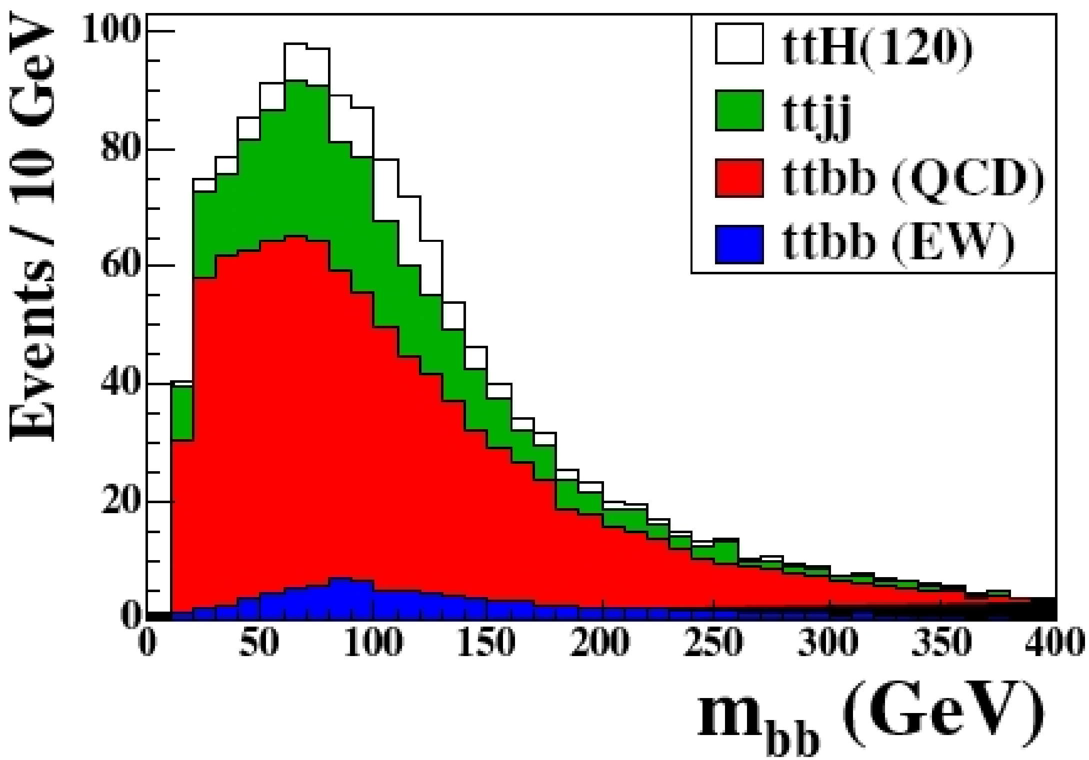


Unique way to measure top quark Yukawa coupling

Early studies looked promising

BUT…Large QCD background to tth

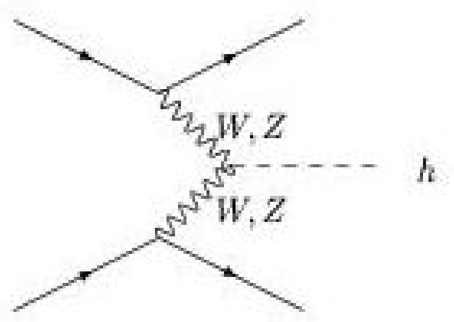
Current $t\bar{t}H, H \to b\bar{b}$ outlook: (30 fb^{-1})

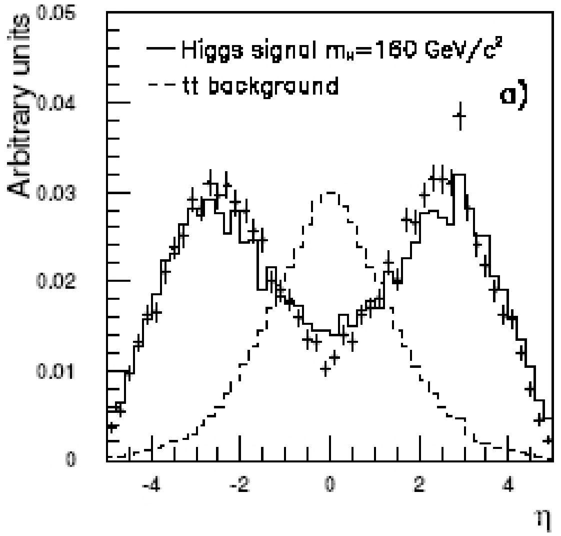


S/B=1/6 for M_h=120 GeV

Vector Boson Fusion

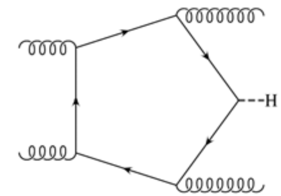
- Outgoing jets are mostly forward and can be tagged
- Vector boson fusion and QCD background look different





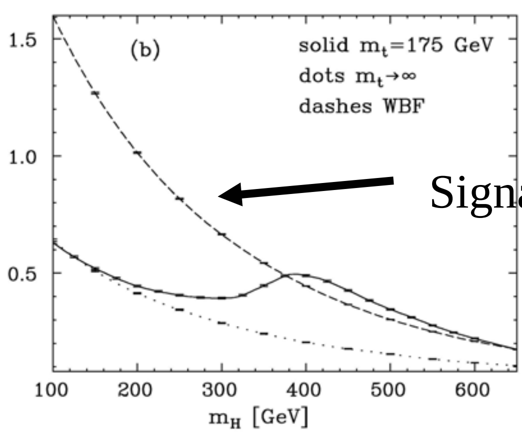
Vector Boson Fusion

- Identify signal with forward jet tagging and central jet veto
- Large Higgs + 2 jet background from $gg \to ggh$
- Kinematic cuts effective at identifying signal



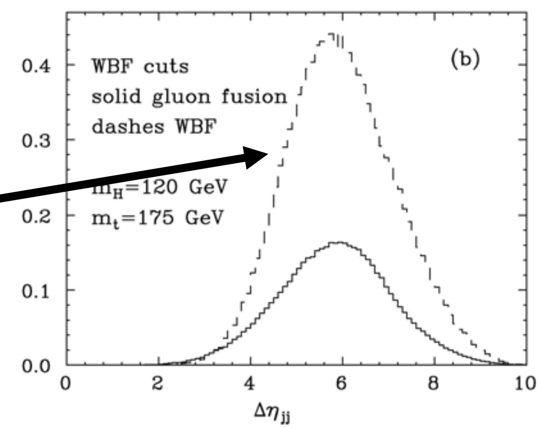
Higgs + 2 jet Production

σ



Signal from WBF after cuts

Rapidity between outgoing jets



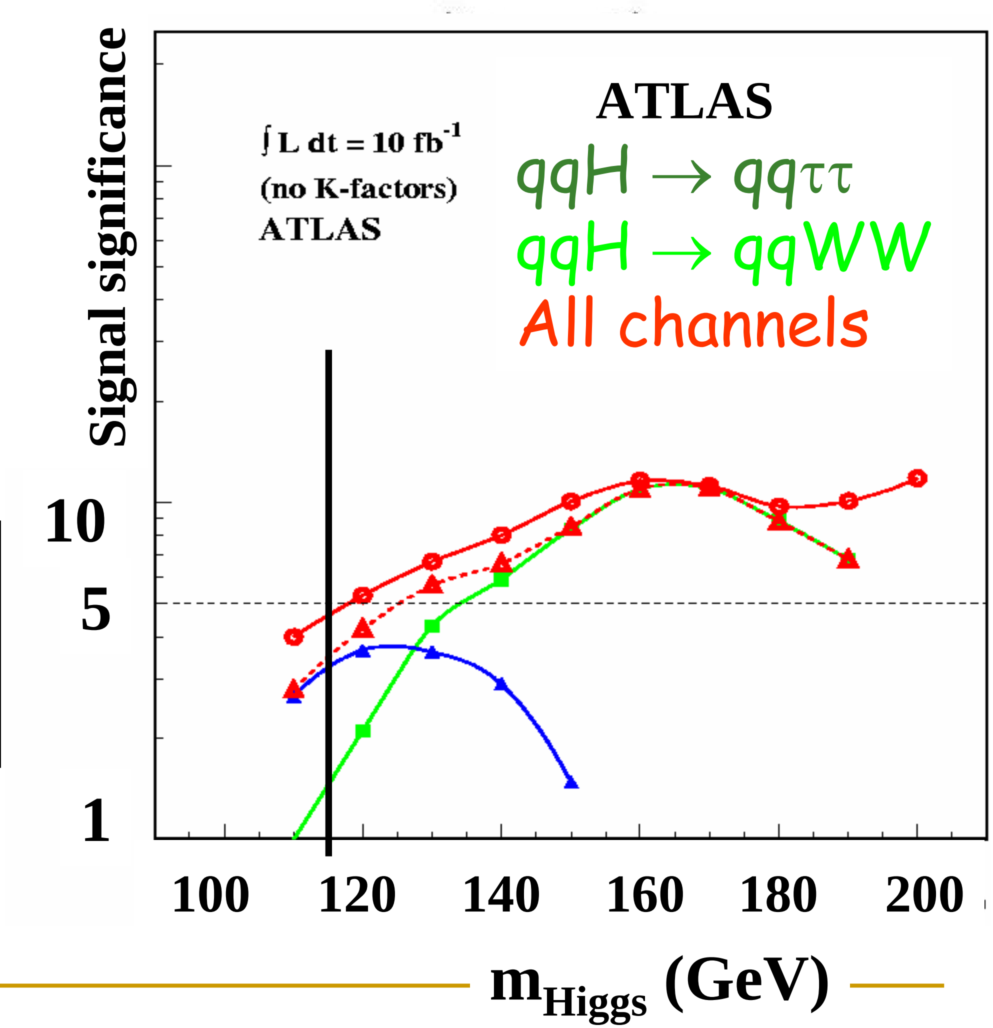
Vector Boson Fusion for light Higgs

➢For M_h = 115 GeV combined significance ~ 5σ

Vector boson fusion effective for measuring Higgs couplings

➢Proportional to g_{WWh} and g_{ZZh}

➢Often assume they are in SU(2) ratio: $g_{WWh}/g_{ZZh}=\cos^2\theta_W$



Vector Boson Fusion for Heavy Higgs

200 GeV < M_h < 600 GeV:

- discovery in $h \to ZZ \to l^+l^- l^+l^-$

•Background smaller than signal

•Higgs width larger than experimental resolution (M_h > 300 GeV)

- confirmation in $h \to ZZ \to l^+l^- jj$ channel

M_h > 600 GeV:

4 lepton channel statistically limited

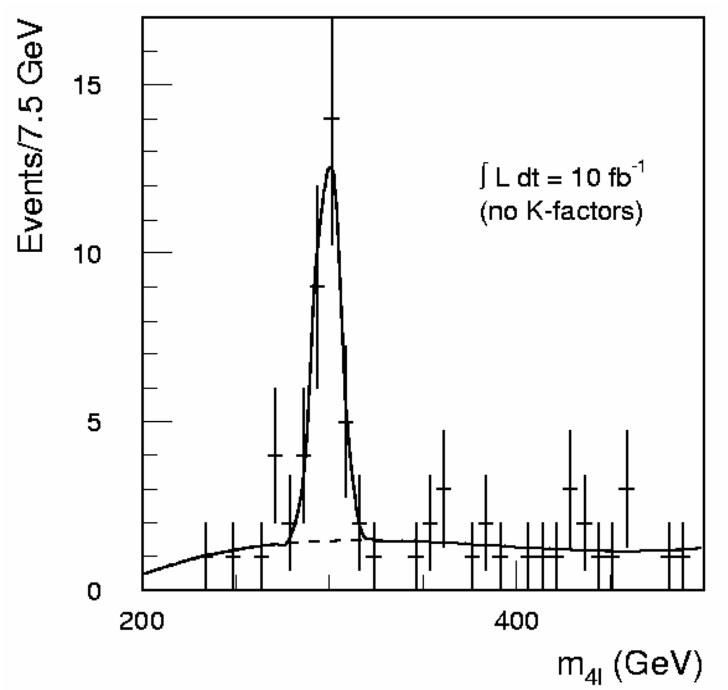
$h \to ZZ \to l^+l^- \nu\nu$

$h \to ZZ \to l^+l^- jj$, $h \to WW \to l\,\nu jj$

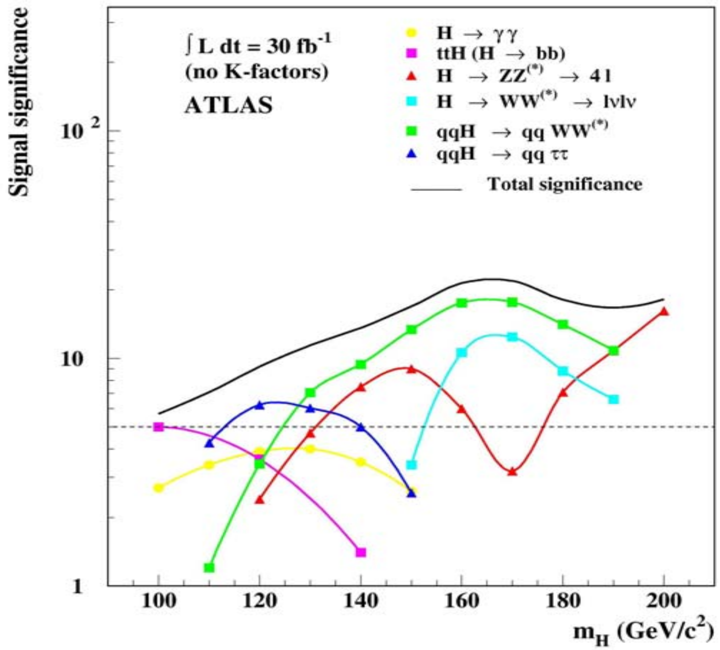
-150 times larger BR than 4l channel

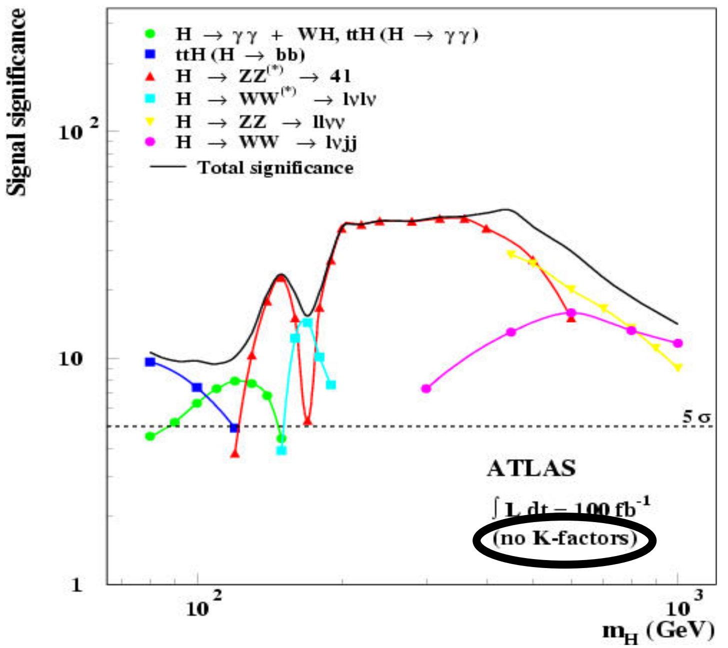
Gold-plated

$h \to ZZ \to l^+l^- l^+l^-$



If there is a light SM Higgs, we'll find it at the LHC





No holes in M_h coverage

If we find a "Higgs-like" object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
  - Is it the SM Higgs?
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)
  - etc

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

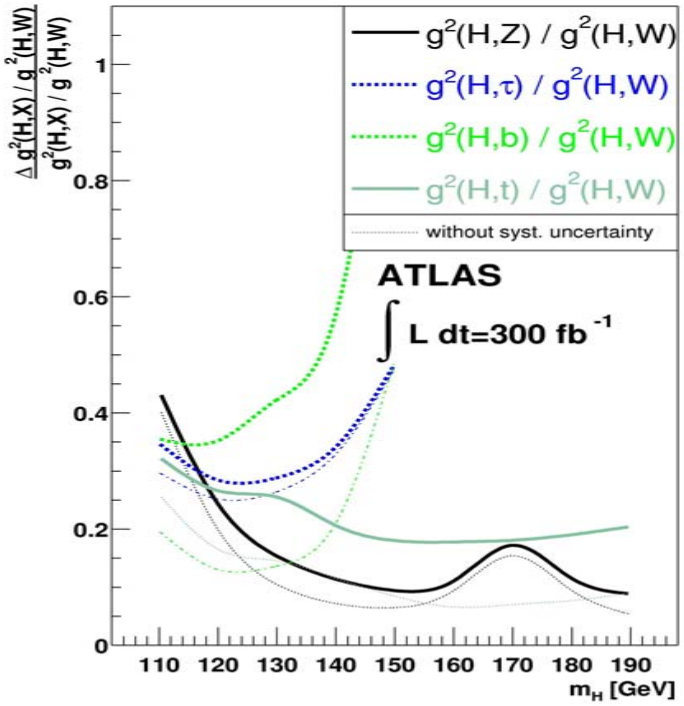
- Measure self interactions

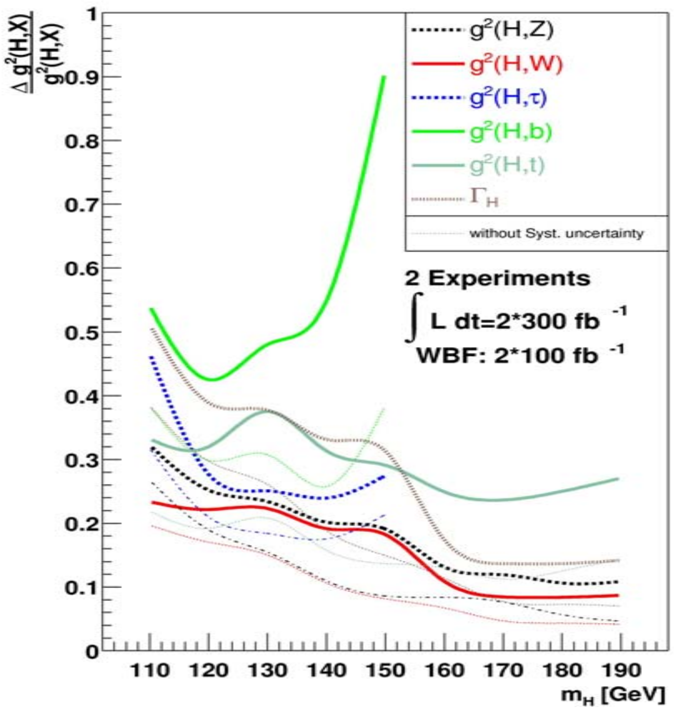
$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

Very hard at hadron collider

Absolute measurements of Higgs couplings

- Ratios of couplings more precisely measured than absolute couplings
- 10-40% measurements of most couplings

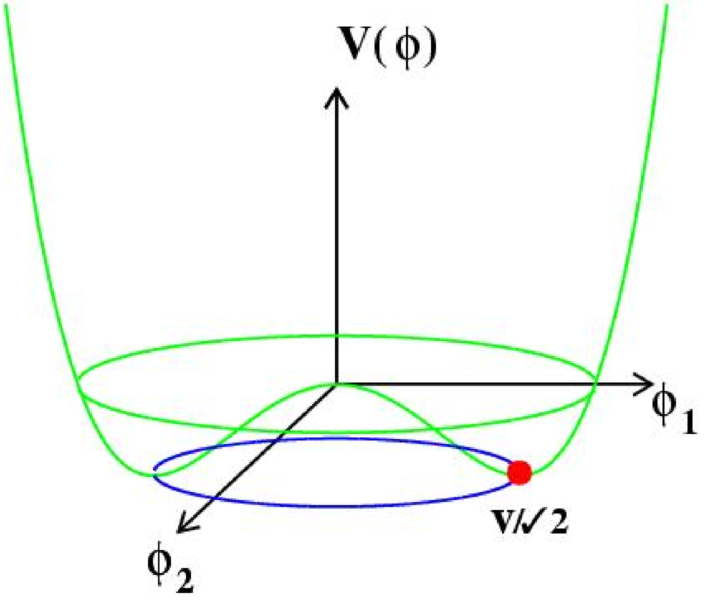




Can we reconstruct the Higgs potential?

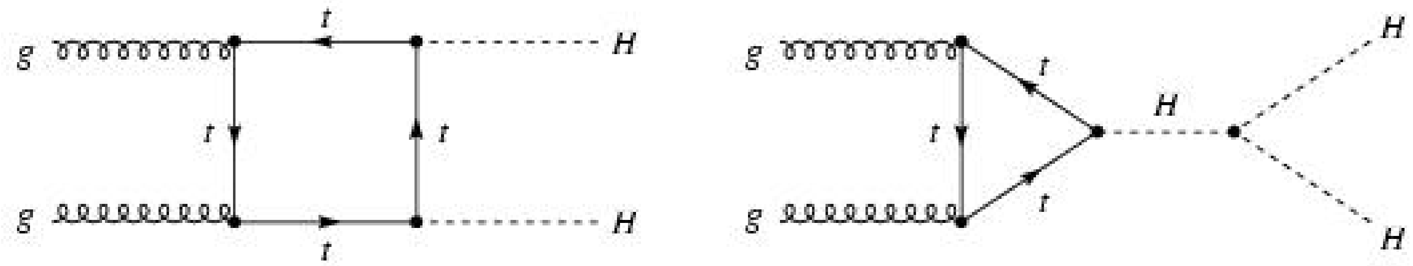
$$V = \frac{M_h{}^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

$$\boxed{SM : \lambda_3 = \lambda_4 = \frac{M_h{}^2}{2v^2}}$$



- Fundamental test of model!
- We have no idea how to measure λ_4

Reconstructing the Higgs potential



- λ_3 requires 2 Higgs production
- M_h<140 GeV, $h \to b\bar{b}b\bar{b}$
- Overwhelming QCD background
- Easier at higher M_h

Can determine whether $\lambda_3=0$ at 95% cl with 300 fb^{-1} for $150 < M_h < 200$ GeV

Higgs measurements test model!

- Supersymmetric models are our favorite comparison
- SUSY Higgs sector
  - At least 2 Higgs doublets
    - SM masses from

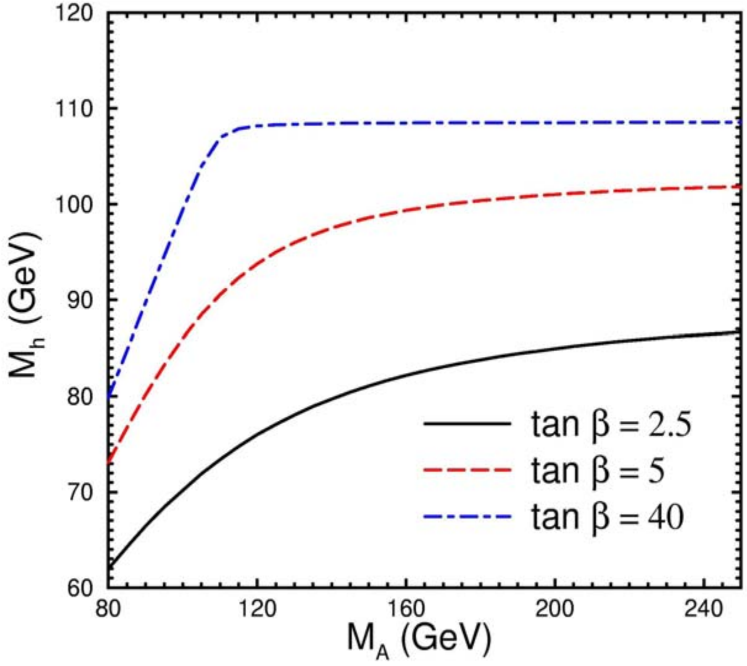
$$L = -g_d \overline{Q}_L \Phi d_R - g_u \overline{Q}_L \Phi^c u_R + h.c.$$

    - Φ^c term not allowed in SUSY models: Need second Higgs doublet with opposite hypercharge
  - 5 physical Higgs: $h^0, H^0, A^0, H^\pm$

SUSY Higgs

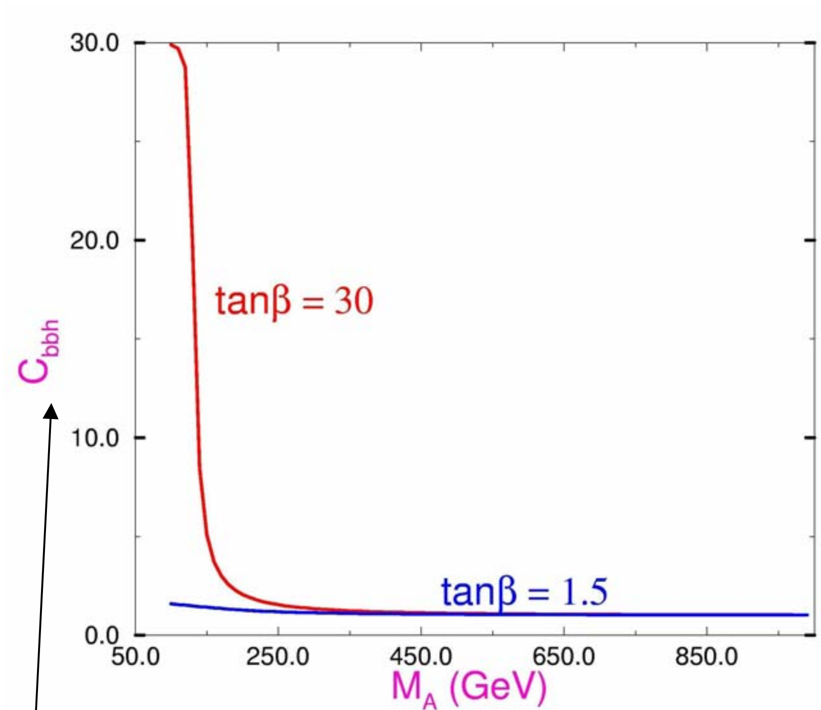
- General 2 Higgs doublet potential has 6 couplings and a phase
- SUSY Higgs potential has only 2 couplings
- Take these to be ***M_A and tanβ***
  - At tree level Higgs couplings, neutral and charged Higgs masses are predicted
  - Lightest Higgs mass has upper limit

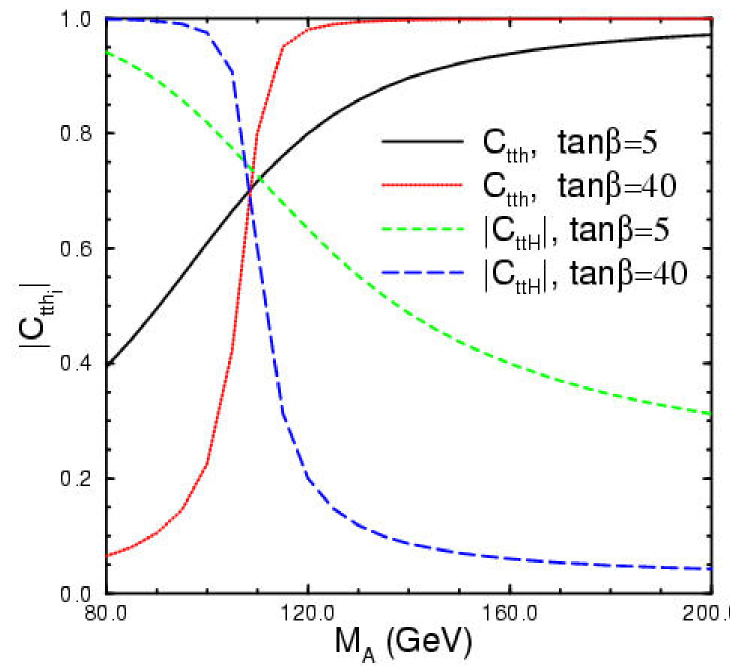
Upper Limit on Higgs Mass in SUSY Models



Can tune parameters, but always have upper limit below M_h~130 GeV

Higgs Couplings very different from SM in SUSY Models

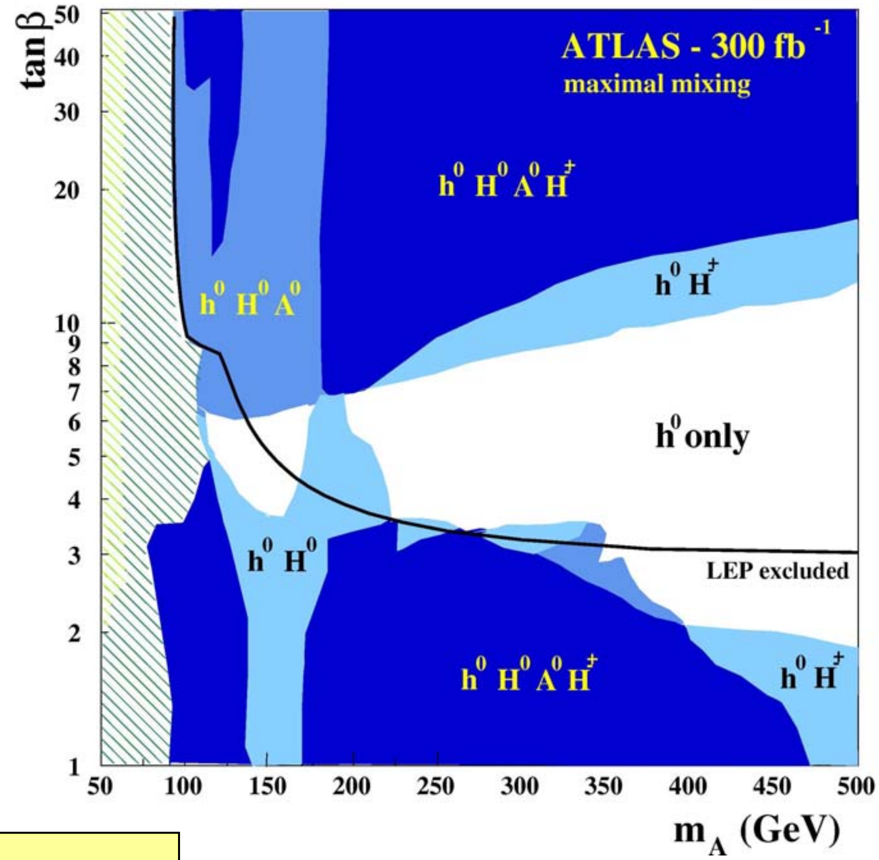




Ratio of h coupling to b's in SUSY model to that of SM

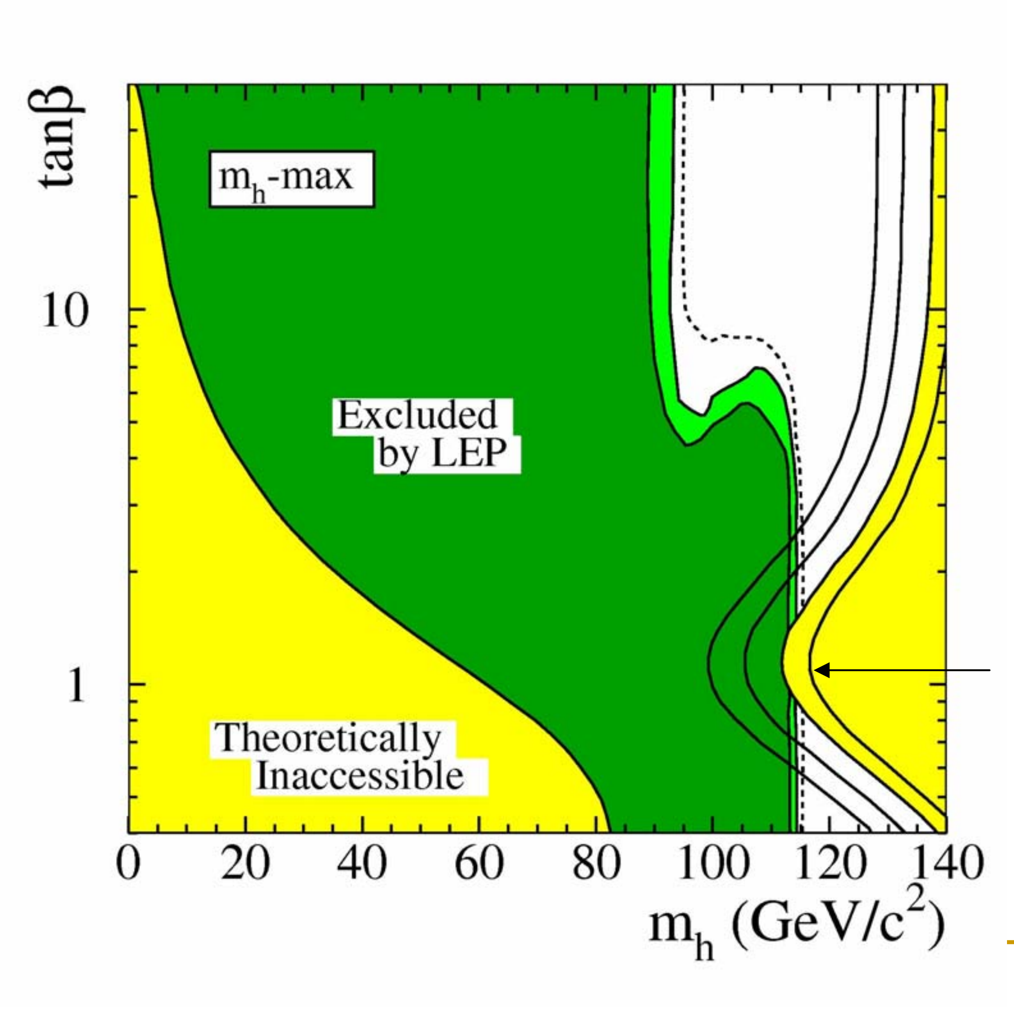
MSSM discovery

- For large fraction of M_A-$\tan\beta$ space, more than one Higgs boson is observable
- For $M_A \rightarrow \propto$, MSSM becomes SM-like
- Plot shows regions where Higgs particles can be observed with > 5σ



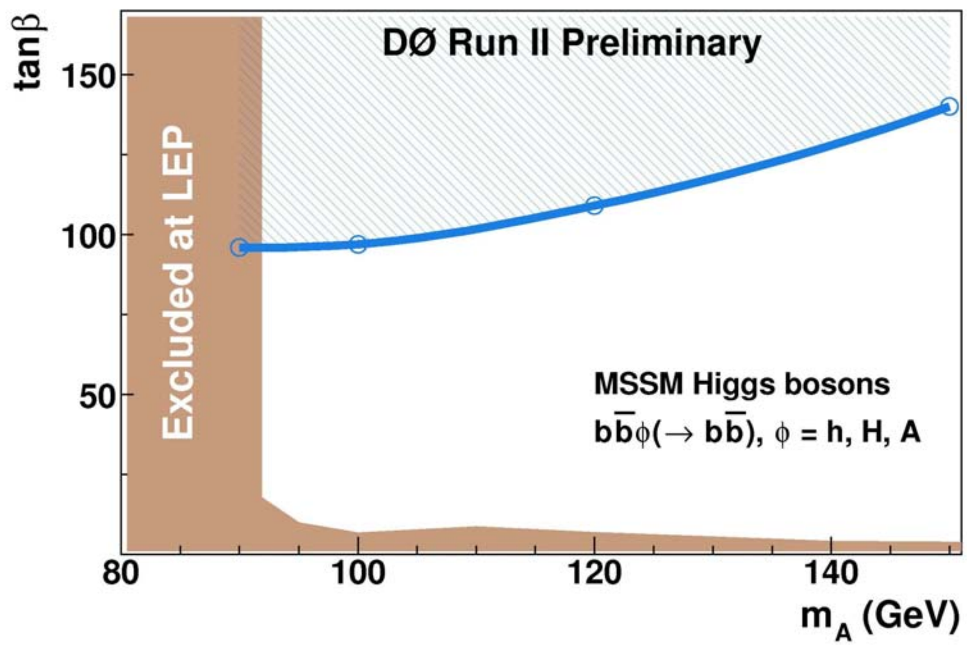
Need to observe multiple Higgs bosons and measure their couplings

Limits on SUSY Higgs from LEP



M_t=169.3,174.3, 179.3, 183 GeV

New Discovery Channels in SUSY



Conclusion

The Higgs boson is the final missing link in the SM